

# Materials Issues Associated with EGR Systems

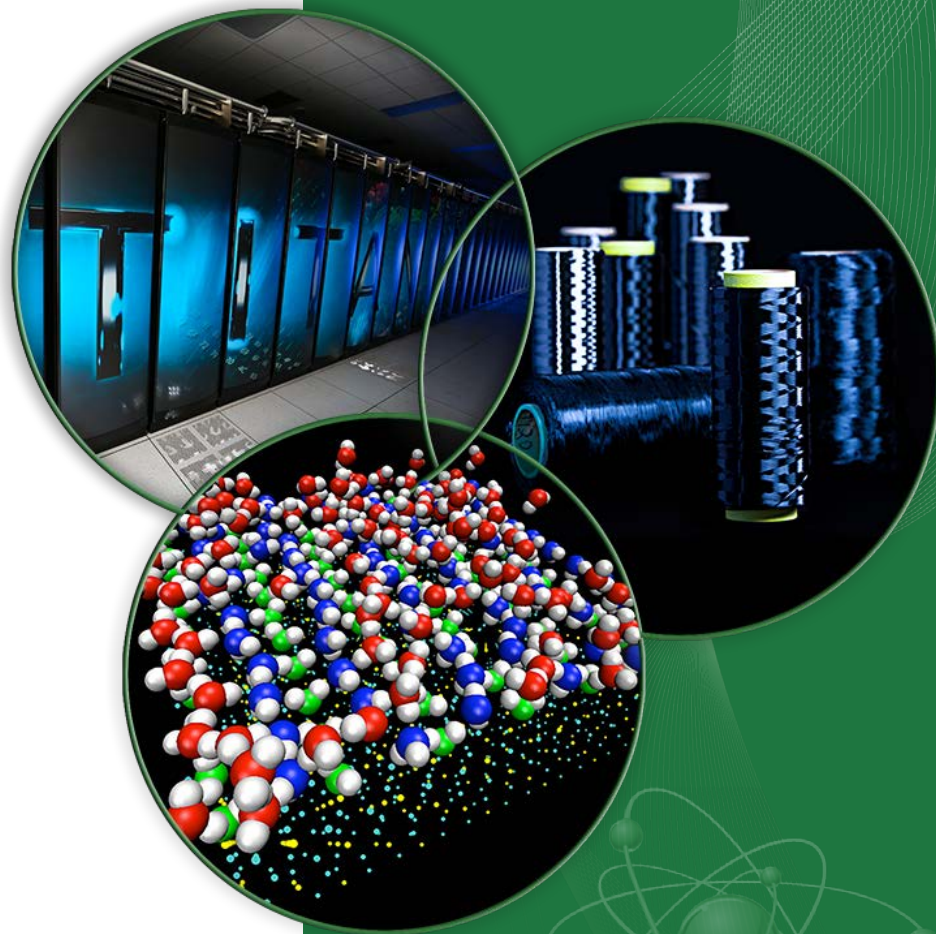
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Project ID# PM009

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# Overview

## Timeline

- Start: FY09
- End: FY17
- 72% complete

## Budget

- Total Project Funding
  - DOE-\$1960 K
- Funding received:
  - FY13: \$170K
  - FY14: \$184K
  - FY15: \$0K (\$130K expected)

## Barrier

### (Multi-Year Program Plan)

- Meeting EPA standards for NOx with little or no fuel economy penalty will be a key factor for market entry of advanced combustion engines.
- Improved efficiency and emission reduction in advanced combustion engines will require exhaust gas recirculation (EGR) to operate over a wider range of engine speed/load conditions.

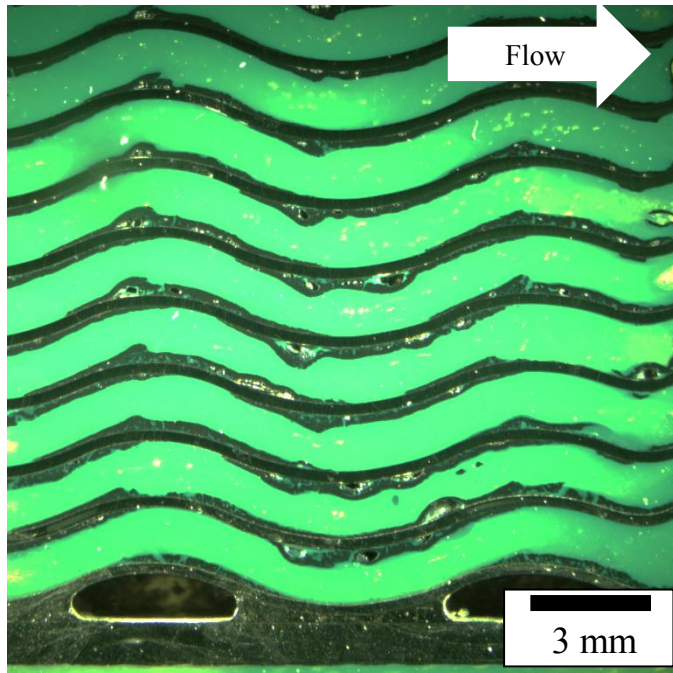
## Partners

### All U.S. Diesel Engine Manufacturers:

- Caterpillar, Cummins, Detroit Diesel, Ford, GM, John Deere, Modine, Navistar, PACCAR and Volvo/Mack
- US Army

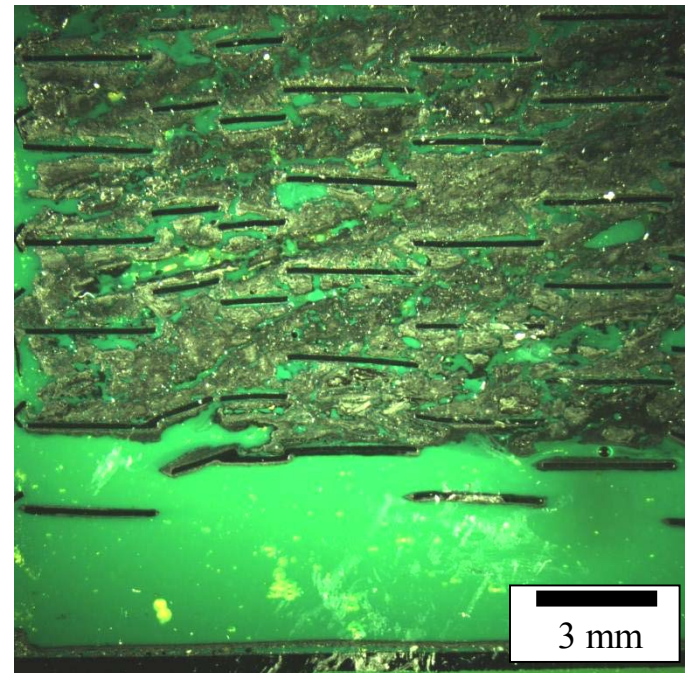
# Background: Exhaust Gas Recirculation Cooler Fouling Causes greater than 1% Loss of Brake Thermal Efficiency

Typical Fouling



- Deposits reduce cooling effectiveness, and increase the back pressure leading to lower efficiency.
- Low-density, low-K, powdery deposit.
- May be mitigated by changes in cooler geometry or engine operation.

Loss of Flow (Plugging)



- Deposits form plugs strong enough to occlude gas passages.
- Usually evidence of large hydrocarbon influence.
- Lacquer-like or tar-like consistency.

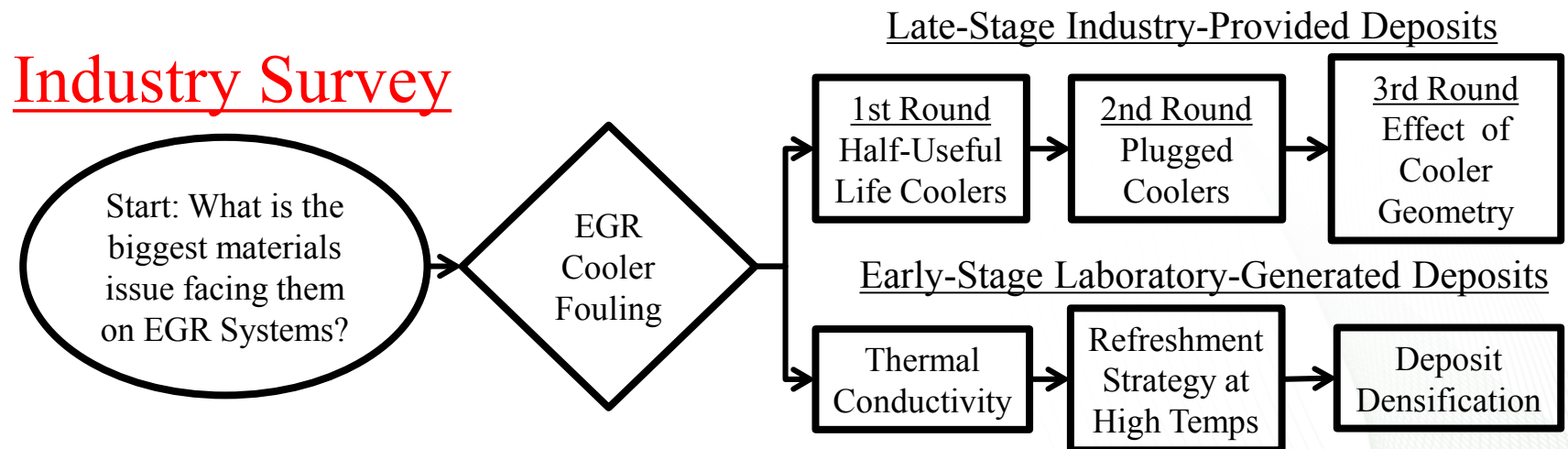


# Relevance: Soot/HC deposits are a perennial, industry-wide problem

- This precompetitive research comes at the problem from a materials perspective seeking to measure the properties of real-world deposits as well as changes in laboratory-generated deposits under different operating conditions.
- Future low temperature combustion strategies will result in more hydrocarbon, exacerbating the problem and causing it to spread to components presently unaffected (turbocharger).
- Waste-heat recovery approaches will be hindered by fouling.

# Objectives: To mitigate EGR cooler fouling and reduce its impact on efficiency and emissions

1. Characterize the thermo-physical properties of the deposit under different operating conditions
  - Industry-provided late-stage deposits.
  - Early-stage deposits produced at ORNL.
2. Develop a protocol for refreshing the EGR cooler during use.
3. Determine novel cooler geometries that will promote deposit removal.



# FY15 Milestones

## Task Title

**Q1: Deposit thickness will be measured on two Modine tubes (one a production geometry and the other an experimental geometry) as a function of location. (COMPLETED)**

**Q2: Measure deposit density changes caused by temperature and water condensation under controlled conditions. (COMPLETED)**

**Q3: Deposit thickness will be measured on cross-sectioned samples generated by John Deere at various engine set-points. (ON TRACK)**

**Q4: The annual report will be submitted**

# Approach

- Experimental Equipment for Deposit Formation and Aging
  - Ford 6.4-L engine to form deposits on model cooler tubes.
  - Portable gas-manifold with high temperature stage for in situ visualization of deposit morphological changes.
- Obtain Industry-Provided Coolers representing specific applications
  - Two rounds of forensic analyses of 22 fouled EGR coolers have been completed.
- Active Control: Explore Potential Refreshment Strategies
  - High-temperature spallation.
  - Low-temperature water condensation.
- Passive Control: Investigate the role of cooler geometry on deposit removal.



New

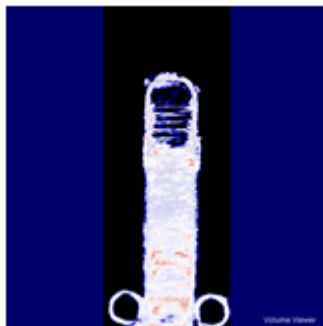


New

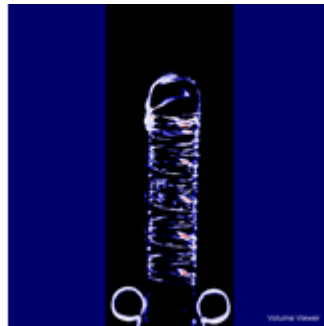
# Previous Technical Accomplishments (FY13&14)

## Neutron Tomography used to Image Deposits

Fouled

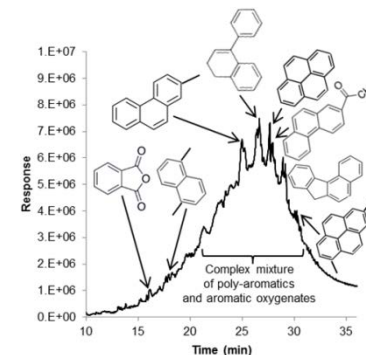
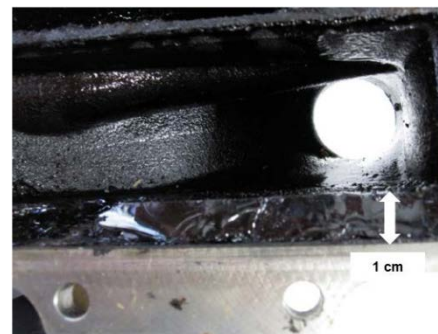


Cleaned



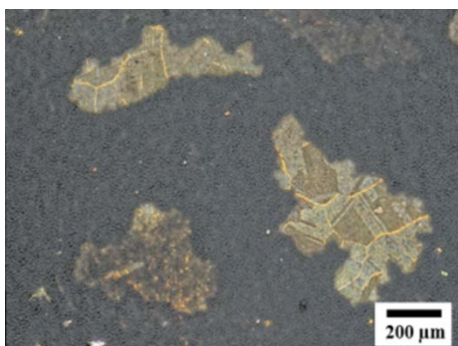
Lance, M.J., Bilheux, H., Bilheux, J.C., Voisin, S., Sluder, C.S. and Stevenson, J., "Neutron Tomography of Exhaust Gas Recirculation Cooler Deposits," SAE Technical Paper 2014-01-0628.

## Identified source of Lacquer Deposits



Lance, M.J., Storey, J., Lewis, S. and Sluder, C.S., "Analysis of Lacquer Deposits and Plugging Found in Field-Tested EGR Coolers," SAE Technical Paper 2014-01-0629.

## EGR Cooler Refreshment with John Deere



Deposit spallation occurred with high inlet gas temperatures and high flow rates

Lance, M.J., Watkins, B.R., Kaiser, M., Ponnaiyan, A., Storey, J.M.E., Sluder, C.S., "Microstructural Analysis of Deposits on Heavy-Duty EGR Coolers," SAE Technical Paper 2013-01-1288.

## Surface Treatments did not Reduce Fouling

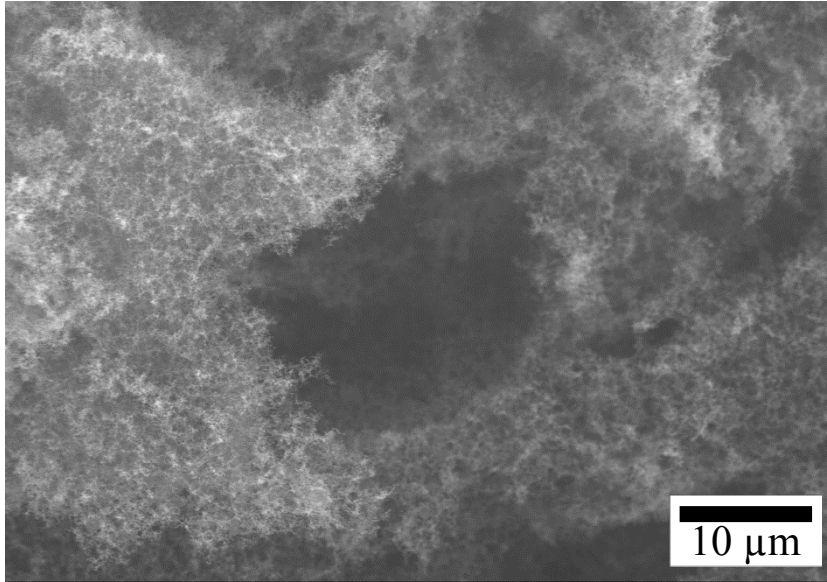
Tube type	Mass gain, mg/cm <sup>2</sup>	Effectiveness loss, %
Plain 316 SS	0.598	16.7
Polished SS	0.598	17.9
Al <sub>2</sub> O <sub>3</sub> -BN	0.601	19.5
Ni-Teflon®	0.600	19.4
SiO <sub>2</sub> -Si-O	0.303	16.9

Storey, J.M.E., Sluder, C.S., Lance, M.J., Styles, D.J., Simko, S.J., "Exhaust Gas Recirculation Cooler Fouling in Diesel Applications: Fundamental Studies of Deposit Properties and Microstructure," *Heat Transfer Engineering* **34** [8-9] 655-664 (2013).

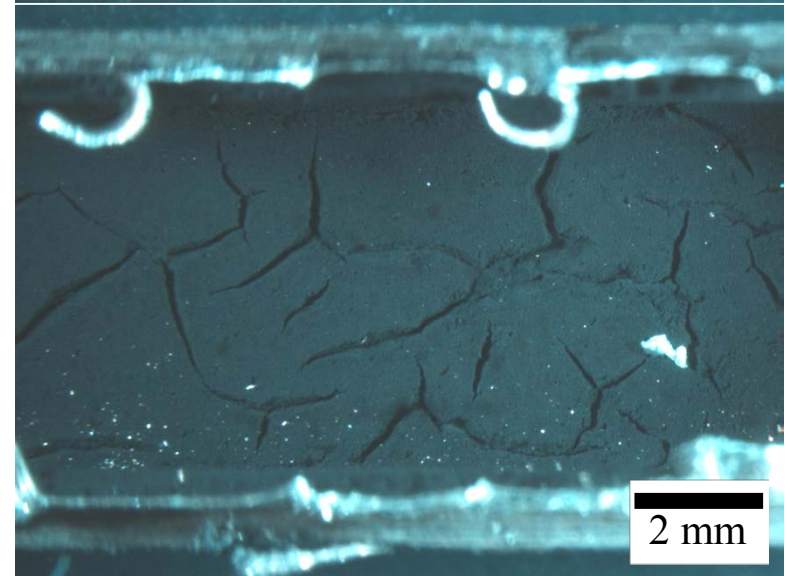


# Technical Accomplishment: Deposits formed using an EGR tube sampler were observed to form mud cracks in ambient air.

High Magnification Image



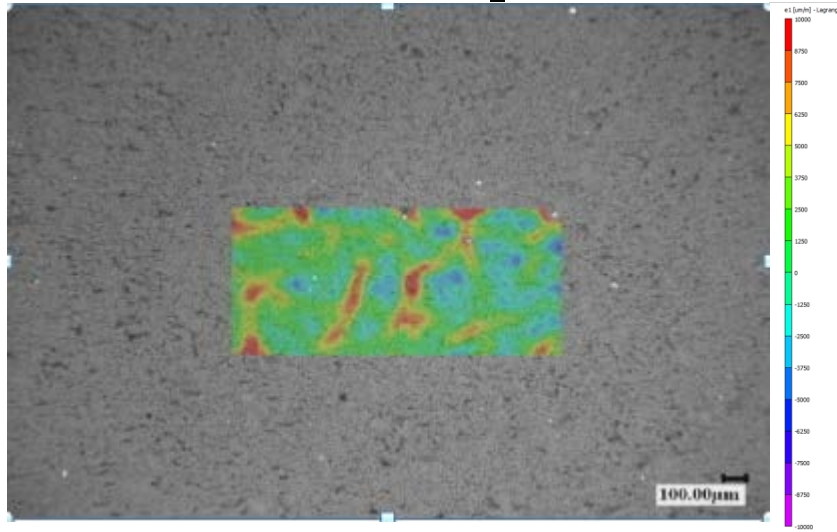
Mud-cracking after 3 weeks in ambient air



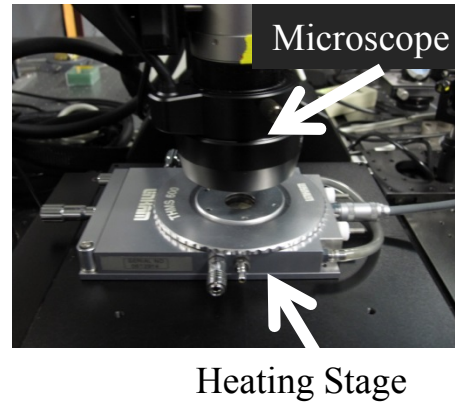
- Deposits were formed under two conditions that simulate heavy-duty and light-duty operation.
- The deposit formed mud cracks in ambient air suggesting that it is shrinking.
- Deposit is ~98% porous: Can we operate the engine in a way that densifies the deposit thereby improving its thermal properties?

# Technical Accomplishment: Digital image correlation (DIC) was used to measure in situ deposit densification under different conditions

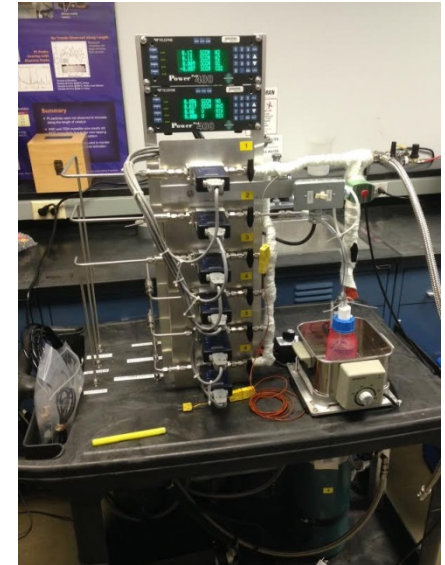
Deposit heated in N<sub>2</sub> to 300 °C



In situ test cell

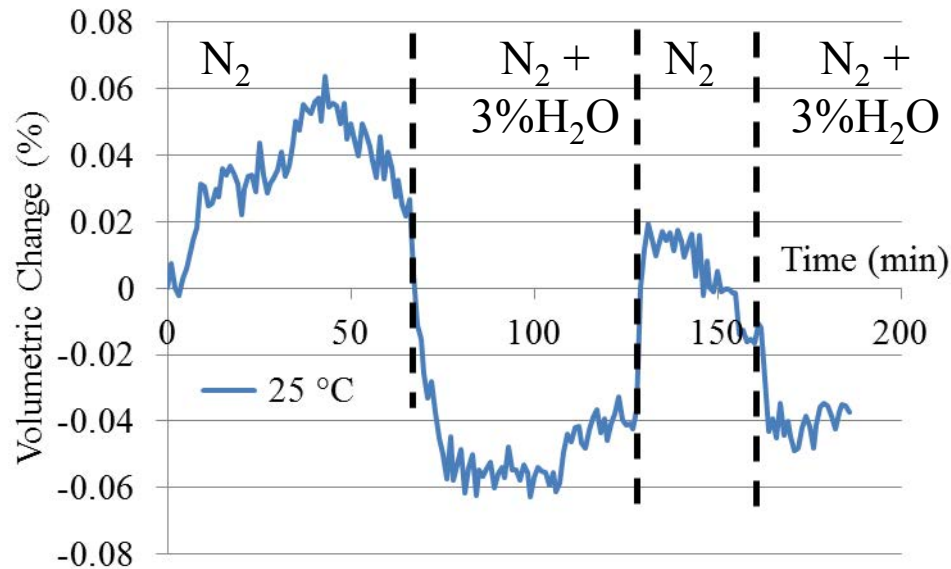


Portable Gas Manifold



- Deformation of deposit surface was monitored using a non-contact method: digital image correlation (DIC).
- A portable gas manifold was used to increase the relative humidity to 100% and the deposit temperature was controlled using the Linkam stage in order to simulate possible refreshment conditions for EGR coolers.

# Technical Accomplishment: Deposit density is dependent upon the relative humidity

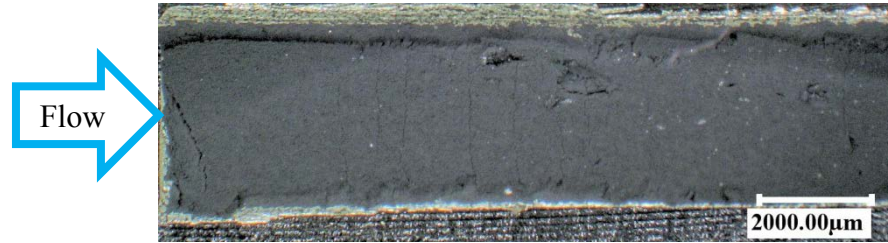


- At room temperature, the deposit shrank when immersed in wet air and expanded again in dry air. This is likely related to the effect of water surface tension on the particulate matter.
- In an EGR cooler, the inlet gas contains  $\sim 10\%$   $H_2O$  which will promote deposit densification. Future work will focus on heating the inlet gas to increase the water content thereby better simulating real-world conditions.

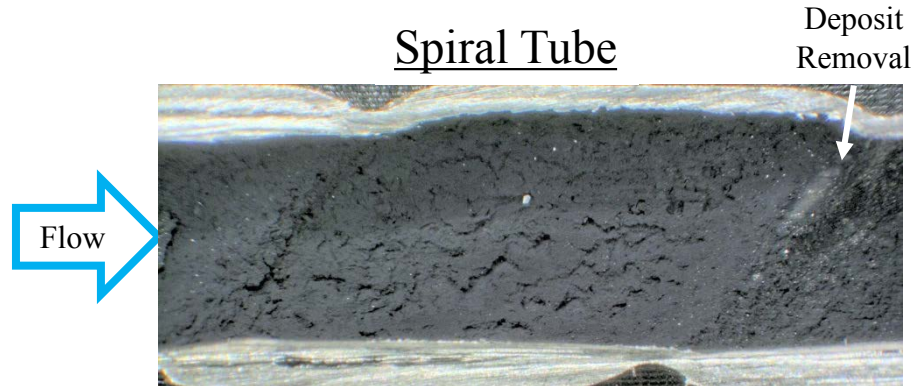


# Technical Accomplishment: Cooler turbulence promotes deposit removal

Flat Tube



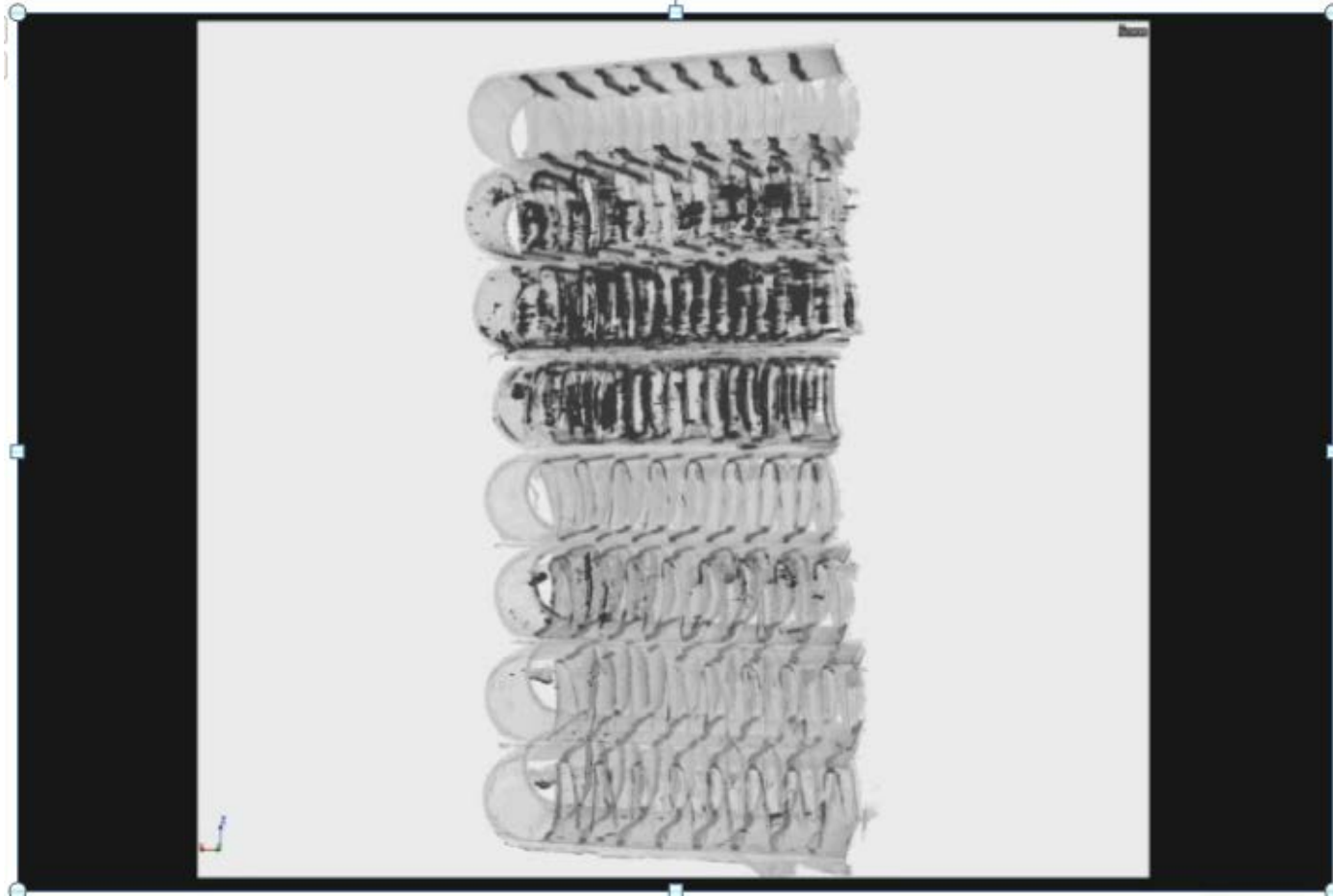
Spiral Tube



- There may be an optimum cooler geometry that results in high heat transfer and high deposit removal.
- Need to measure the deposit thickness with respect to the cooler geometry.
- Neutrons, which are attenuated by hydrogen, are useful for imaging deposit location on plugged coolers but failed to image low HC deposits.



# Technical Accomplishment: Deposit was coated with a Gd and imaged using neutron tomography



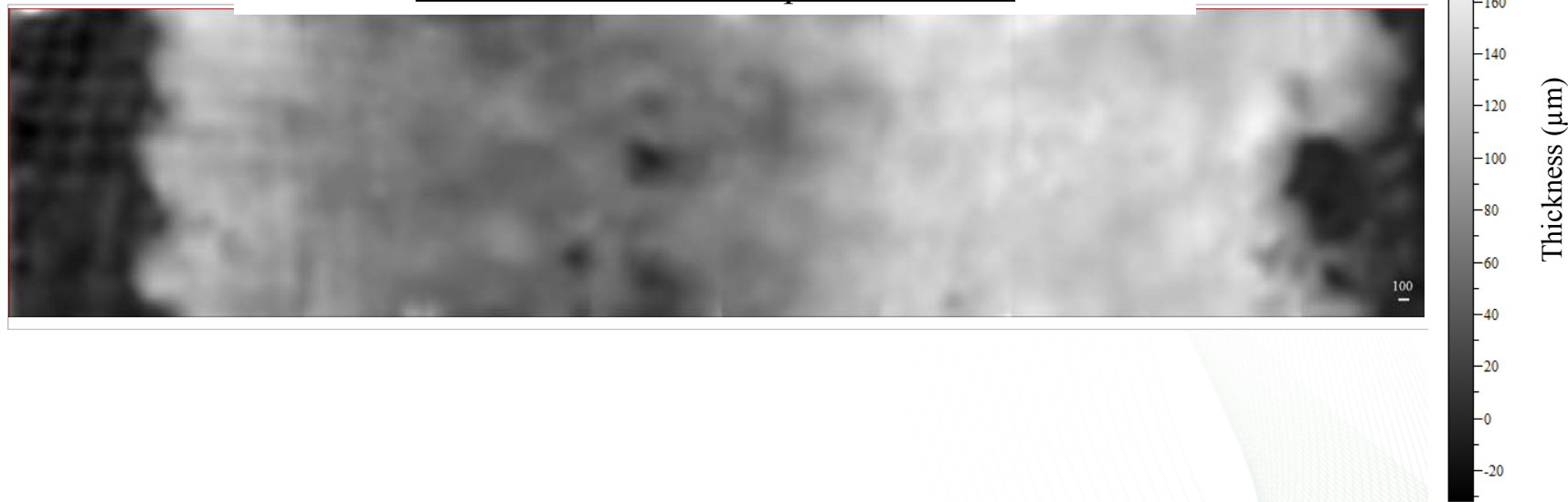
- As a proof of concept, the deposit was immersed in a gadolinium containing fog (Gd is a strong attenuator of neutrons) which enhanced the neutron attenuation allowing the deposit location to be observed as a function of geometry.

# Technical Accomplishment: The effect of cooler turbulation on the deposition and removal of the deposit was studied using an optical profilometer

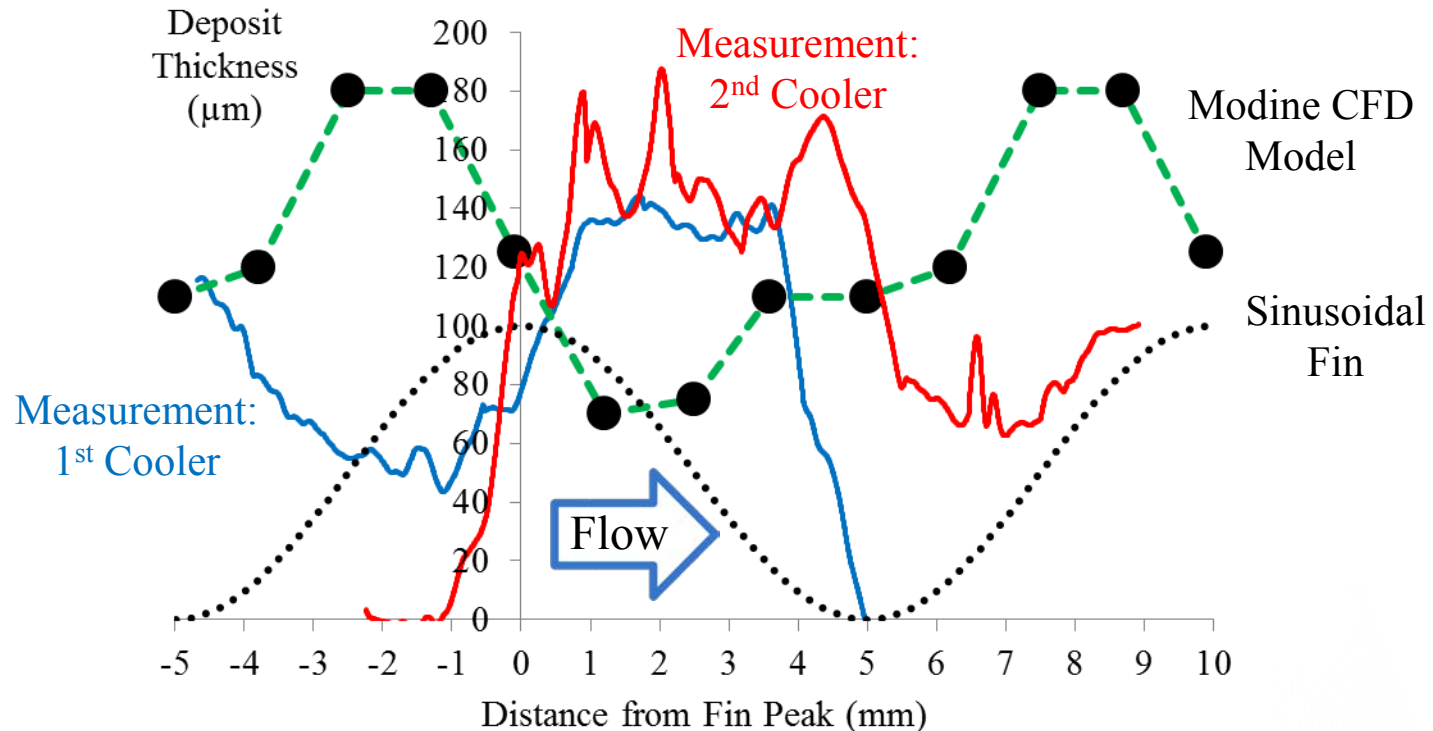
A single sinusoidal fin of a cooler provided by Modine and fouled at John Deere



The difference is the deposit thickness

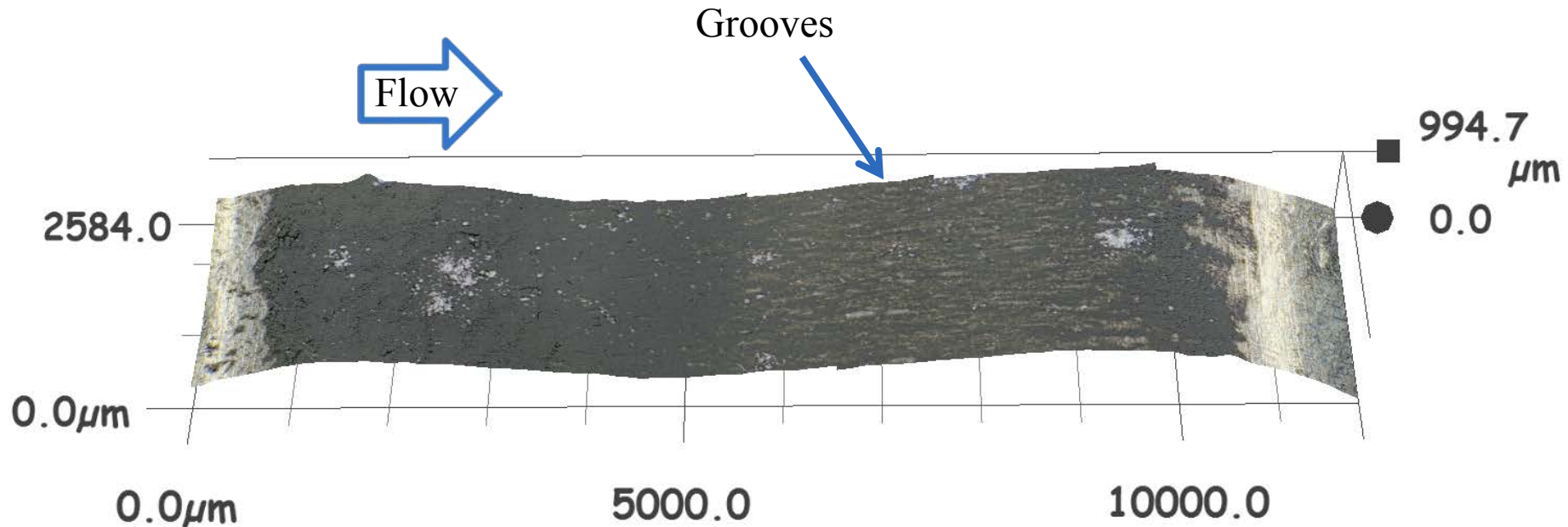


# Thickness measurements were compared to computational fluid dynamic (CFD) modelling



- CFD model predicted the thickest deposit upstream from the peak of the fin.
- Measurements contradicted the CFD model with the thickest deposit occurring downstream from the peak.
- A second geometry exhibited the same trend.

On the upstream side of the peak there are grooves in the deposit that indicate shear removal has occurred



- The highest heat transfer occurs at the upstream side of the peak where the boundary layer is the thinnest. The CFD model also predicted that the thin boundary layer will result in the most deposition.
- Our results significantly alter this model of fouling and show the importance of shear forces and their interaction with turbulence structures for controlling the deposit thickness and hence the impact of fouling on EGR performance.



# Responses to Previous Year Reviewers' Comments

Comment: “where there was little discussion on proposed material solutions that would reduce the EGR fouling. The reviewer questioned if other material could not be identified for side-by-side testing, which could have already started.”

Response: Previous published work focused on a coatings solution but it was found that coating the metal substrate had no effect on fouling rate. Since a coating was ineffective, it is unlikely that changing the base alloy would reduce fouling either.

Comment: “The reviewer opined that it was a pity that the test with the neutron technique did not give the expected answers, and questioned if it was possible to give some guidance to when this new technology can or cannot be used.”

Response: In order for this approach to work, a hydrocarbon concentration of at least 10% would have to be achieved. Otherwise, as shown here, using tracers such as Gd may allow one to image the deposit with low HC content.

Comment: “Modine, was not mentioned anymore as it was in 2013, even though their logo was on one of the final sheets.”

Reponses: Modine has been contacted and are contributing both materials for testing and CFD modeling of deposit formation as discussed in the previous slides.

# Collaborations: EGR Materials Advisory Team

- Modine: Provided EGR tubes of 2 different geometries and computational fluid dynamics (CFD) modeling.
- John Deere: Ran engine tests that resulted in fouled EGR coolers.
- The EGR team advise the project and provide real-world coolers:
  - Caterpillar
  - Cummins
  - Detroit Diesel
  - Ford
  - GM
  - John Deere
  - Navistar
  - PACCAR
  - Volvo/Mack

# Remaining Challenges and Barriers

- The testing in ambient air resulted in densification too small to significantly improve the thermal conductivity of the deposit.
- In order to better understand the role of cooler geometry in soot deposition and removal and to make recommendations to our industry collaborators, computational fluid dynamics (CFD) modeling must be conducted in conjunction with deposit thickness measurements under different operating conditions.

# Future Work

- Deposit densification will be measured with inlet gas containing up to 10% H<sub>2</sub>O and with deposit temperatures more relevant to industry (40 to 90°C).
- EGR coolers fouled at John Deere using a 5-factor, 3-level design of experiments with the following variables: (1) flow rate, (2) inlet gas temperature, (3) coolant temperature, (4) soot level, and (5) hydrocarbon concentration will be used to improve our understanding of the role of geometry on deposit formation and removal. Results will be compared to CFD modeling from Modine.

# Summary

## Relevance

EGR fouling results in  $>1\%$  loss in brake thermal efficiency.

## Approach

Active Control: Low-temperature water condensation.

Passive Control: The effect of cooler geometry on fouling studied with deposit thickness measurements compared to CFD modeling.

## Technical Accomplishments and Progress

The DIC technique was used to measure deposit densification when immersed in wet air which will lead to higher thermal conductivities.

Deposit thickness measurements contradicted CFD modeling illustrating the central importance of shear forces and cooler geometry in fouling.

## Collaboration

With entire diesel engine community; leveraging their in-kind investments of expertise, testing and materials.

## Proposed Future Work

Use more aggressive water condensation testing to promote deposit densification and characterize the interaction between cooler geometry and engine operating conditions.